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Technical Evaluation Report

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OBJECTIVES

The goal of the NATO-RTO is to conduct and promote cooperative research and information exchange within NATO and with its Partners. To achieve this goal, the RTO has set out three key objectives:

- To support the development and effective use of national defence R&T and thus maintain a technological lead within the alliance.
- To meet the military needs of the alliance.
- To provide advice to NATO and national decision-makers.

The requirement for the RTO-AVT-075 Symposium on Monitoring and Management of Gas Turbine Fleets for Extended Life and Reduced Costs grew out of the activities of the RTO Working Group 28. The objective of the symposium was to facilitate additional information exchange to provide professionals responsible for monitoring and management of gas turbine fleets with guidance on existing and proven techniques, and an insight into new technologies and practices planned for future systems. Therefore, the objective of the symposium was assessed as effectively supporting the achievement of RTO's key objectives. The symposium addressed gas turbine life management issues under four session headings:

- Maintenance and Logistics Practices – knowledge of methodologies for forecasting spares requirements, parts tracking and determination of service levels.
- General Design Practices – defining the impact of component deterioration, performance sensitivities to component changes made to improve life, and performance levels required by new or different roles or mission profiles.
- Usage Data and Mission Analysis – information on monitoring systems, translation algorithms, sampling methodologies, design practices, and methodologies for assessing unforeseen in-service usage.
- Life Determination Methodologies – understanding of design models, failure modes, material properties, and life assessment methodologies.

The quality of the written papers and delivery of the presentations conveyed an enormous quantity of valuable information concerning research and development efforts in this area of specific military interest. The benefit of RTO's ability to bring together operators, logisticians, designers, scientists and academics in such highly focused symposia was evident in the lively and thought provoking discussions. In informing those who attended, provoking thought and promoting discussion, and in bringing together this collection of papers for publication and wider distribution, the RTO-AVT-075 Symposium successfully met its objective and contributed to the satisfaction of RTO's key objectives and the achievement of its goal.

CONCLUSIONS

The symposium reaffirmed and raised a number of conclusions on the subject of monitoring and management of gas turbines:

- Replacement of Life Limited Parts (LLPs) constitutes a strong cost of support driver.
- There is scope for life extension of LLPs, especially of older components under the safe-life philosophy.
- Self-reliance in lifing capabilities is important in enabling military gas turbine operators to manage in-service issues.
- Full fleet monitoring is the optimal solution for effective fleet management.
- There is a poor correlation between flight duration and component life usage
- Whilst large quantities of operational and maintenance data are collected and stored, many of the databases have severe limitations that impact on their usage and ability to support data manipulation and extraction of information on which to base fleet management decision-making.
- Data variability hinders analysis and imposes expensive conservatism in lifing methodologies.
- Greater understanding of crack propagation is urgently required and enhanced NDI techniques are essential to support life extension initiatives.
- In considering engine modification or upgrade, the whole of the engine system, including the monitoring functions, has to be considered to ensure that the probability of successful improvements and payback is necessarily high. The monitoring system requires a continuous improvement programme to ensure that fleet management is adequately supported and to realise the benefits of technology insertion.
- Life Cycle Cost (LCC) modelling is essential in supporting the business cases for modification or upgrade and for evaluating the ensuing impact of the investment. This support should be extended to inform decision making on fleet out-of-service dates to ensure that the appropriate level of logistic support is budgeted for.

RECOMMENDATIONS

To enhance monitoring and management of gas turbine fleets for extended life and reduced costs, the RTO's influence may be effectively applied to the promotion of cooperative research and information exchange in the following areas:

- Crack propagation – encourage research into this safety-related, non-competitive area.
- NDT – generate a symposium on critical component specific inspection techniques and residual stress measurement.
- Data transfer/exchange translation methods – research targeting materials and usage/damage databases.
- LCC modelling - generate a symposium.

INTRODUCTION

The continual downward pressure on defence expenditure has resulted in affordability being recognised as a key driver in future air equipment capability strategies and Life Cycle Costs (LCC) being considered with equal weight as performance in modern equipment procurement programmes. The acquisition of an engine and its associated components requires substantial financial outlay, however, it is the operating and support costs that drive the propulsion system to account for large proportions of weapon system LCC, typically 20% to 40% for air weapon platforms.

NATO armed forces specifically require:

- Highly capable forces, exploiting the operational benefits of advanced technology to enable them to make high quality contributions to multinational operations.
- Rapidly deployable forces, able to effectively project power quickly into theatre to prevent crises escalating into conflict.
- Sustainable forces, able to conduct simultaneous or prolonged operations in inhospitable environments.
- Flexible forces, able to fight and win intensive war-fighting operations, yet capable of effectively undertaking operations across the remainder of the crisis spectrum.

Financial constraint ensures that it is not possible to modernise or re-equip across all capability areas and raises the requirement for ageing systems to be retained in service for longer and possibly operated in a more flexible manner than had originally been anticipated. Sustainability of these ageing systems presents a major logistics challenge for fleet managers; they are required to ensure that operational availability remains acceptably high whilst driving support costs to necessarily low levels. With the vast majority of propulsion system LCC being consumed by operation and support activities, it is in the in-service portion of the life cycle where the benefits of advanced technology should yield significant affordability benefits. The motivation for the RTO-AVT-075 Symposium grew out of the activities of the RTO Working Group 28 and its publication of the RTO-TR-28, Recommended Practices for Monitoring Gas Turbine Engine Life Consumption. The aim of this meeting was to promote additional exchange of information on gas turbine life management techniques for improved support of existing in-service systems. Although the meeting was not focused on the development of new gas turbines, reviews of emerging systems were valuable in illustrating how previous monitoring shortfalls are being addressed for next generation equipment and highlighting technological advances that may become available for modification and upgrade programmes.

EVALUATION

The symposium comprised 24 technical papers, presented in 10 sessions under four major session headings. Although three papers were withdrawn, three additional papers were offered to restore the programme and, indeed, make a significant contribution to it. The breadth of the contributor-base, with papers submitted from a wide cross-section of NATO and her allies (Chart 1) and an even wider audience participation, awarded the symposium much credibility in its aim to promote, at a multi-national level, the exchange of research and development information on gas turbine life management techniques.

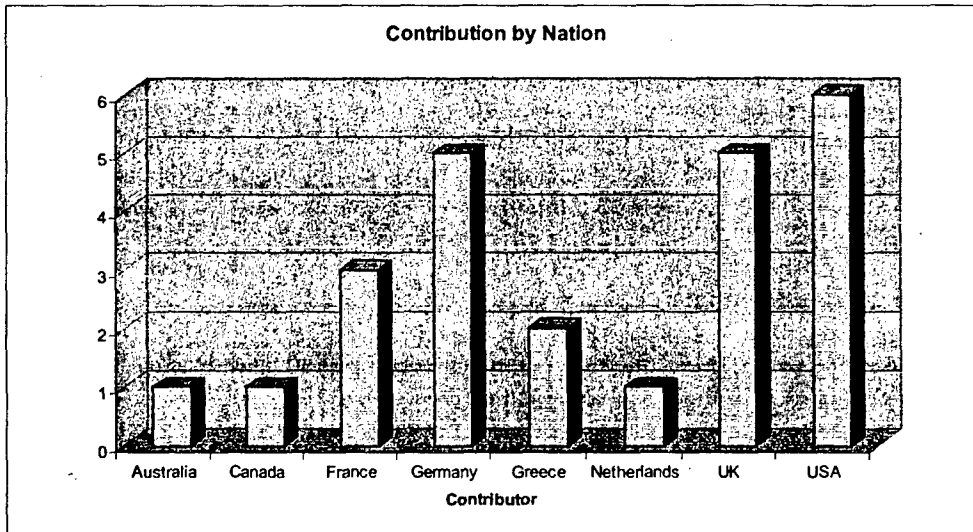


Chart 1

The 'contribution by sector' analysis (Chart 2) confirmed that the customer focus had been strongly represented and that all areas of research and development were able to contribute to the topic. The significant presence of 'independent' organisations was considered to be indicative not only of the openness of this topic to non-military and non-OEM technologies but also of the privatisation of government RTOs

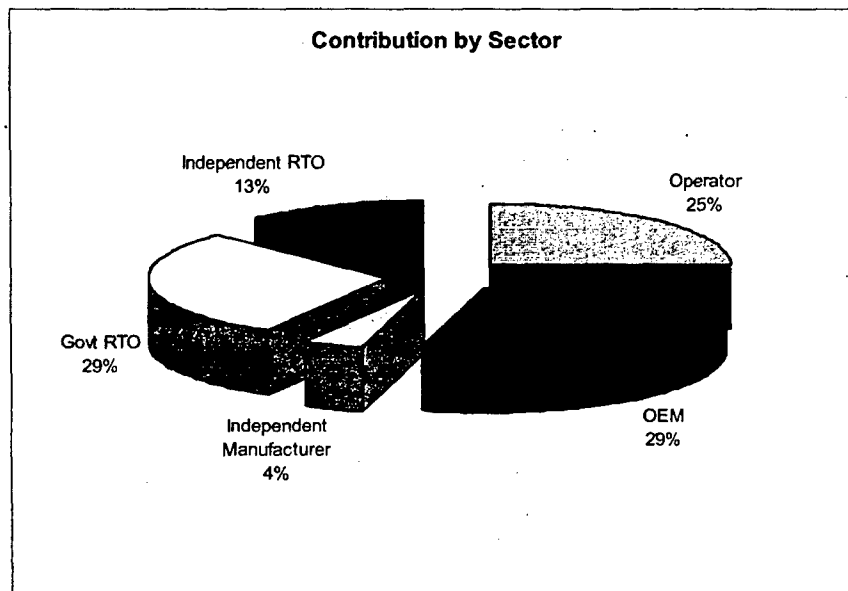


Chart 2.

The symposium content had been arranged to flow from the higher level objectives of maintenance and logistics practice, through general design practices, various approaches to usage data and mission analysis, into the intricacies of component life determination. The desired effect was achieved although the absence of some abstracts and papers for review in advance of the meeting resulted in allocation based only on the title of the paper. For the purposes of evaluation, a slightly revised allocation of papers to that followed by the symposium programme will be applied.

The Meeting was opened with a Plenary Keynote Address that set the scene for the symposium by discussing the management challenge posed by ageing aircraft fleets. This theme was strongly continued in the Keynote Addresses with Mike Botley clearly illustrating the strengths of functional collocation brought about by the

formation of the Warship Support Agency and the move to Integrated Project Teams. He discussed the impact of repair and overhaul studies and the detailed process management that has enabled significant cost and Turn Round Time (TRT) reductions. Inventory, or cost of stock-holding, reductions had also been achieved without reducing the level of operational support. Within this climate of cost reduction and competition, contrary to what might be expected, the relationship with industry had actually been improved through the application of incentivised contracts and partnering principles. Otha Davenport stated that ageing engine programmes always struggle to secure funding for new technology insertion and that, although new roles and manoeuvres and continued demand for performance may impose additional cost, engine support budgets were not factored for any increases during old age. This was contrasted against the many modification programmes, such as retrofitting of modern digital engine control systems, that had demonstrated significant financial and operational benefit. He described how the USAF had embraced the use of an Engine Life Management Plan to provide a comprehensive picture of component life, usage, maintenance, upgrades, wear patterns, deterioration rates etc. The plan is updated on a two-year cycle and is used by skilled engineers and logisticians to produce detailed workscopes for engines passing through overhaul, to achieve build standards matched to the operational requirement. The approach was described as RCM rather than OCM-based and claimed to have doubled engine on-wing life for the C5 fleet.

Maintenance and Logistics Practices

The fleet management practices highlighted in the Keynote Addresses are aimed at developing and concentrating the capabilities for forecasting spares requirements, parts-life tracking and determination of service levels. However, the studies and methodologies necessary to support them require data to fuel the analyses and generate the information upon which appropriate management decisions can be made. Paper 1 provides an insight into the amount of data that is available for the RAF Tornado fleet but also illustrates the difficulties faced in trying to manipulate data for a purpose other than that intended. It was found that data had not been generated and stored with the integrity and granularity necessary for the new purpose and, with it embedded in a multitude of separate databases not designed for the type of interrogation necessary, that the analysis was, at best, arduous and, at worst, unrealistic and misleading; an issue highlighted in a number of other papers.

It is shown that the bulk of RB199 engine support costs for RAF Tornado fleet operations are attributable to the in-service phase. Difficulties in securing full predicted benefits from modification action designed to address durability shortfalls are used to illustrate the importance of adopting a systems approach to the development of any life extension project; the application of skilled engineers and logisticians supported by data from monitoring and trending of both operational and maintenance performance considering the whole engine. This theme was continued in Paper 6, which described the evolution of SNECMA monitoring capabilities in concert with operational maintenance policies, and in Paper 19, in which the reliability-centred approach employed by Turbomeca in developing helicopter engine maintenance strategies was described. Paper 4 expands on the systems approach theme in describing the operation and benefits of a fleet support environment based on pooling of engine assets, utilising a closed-loop management system that confirms the interdependence of engine fleet management and monitoring system performance.

The paper, 'Risk Assessment Methodologies for Fracture Critical Components', discusses the different approaches that must be adopted, depending on the nature of the issue, in quantifying the risk to in-service components from unforeseen damage mechanisms or failure modes. Drawing upon risk analysis experience, the paper introduces a modified decision matrix that offers the flexibility to present the results in the most appropriate format for fleet management decision-making.

General Design Practices

The design and implementation of engine monitoring systems are daunting tasks; Paper 3 draws upon the past 15 years of experience in the introduction and operation of the OLMOS system to discuss the challenge. The paper strongly states that monitoring systems are not one-off improvements. Not only is the system required to respond to changes in the engine, the effects of ageing, modification, and changes in use, but the monitoring system itself requires a development programme to ensure that it is able to meet the increasing demands of the fleet management task. Technology insertion and modifications to improve monitoring capabilities are notoriously

difficult to justify, the payback periods may be extensive and the benefits may be viewed as intangible. However, unless the systems approach to engine modifications is extended to include the monitoring functionality, it is likely that project timescales will be extended and perceived benefits will remain beyond reach; component improvements operated under old lifing methods will never yield the return on investment that justified them. Similarly, advances in monitoring technology or data analysis techniques may be able to eliminate conservatism in the lifing methodology and make significant savings on critical parts replacement costs. This is illustrated by the application of plausibility boundaries to manage usage data scatter; the paper describes how major savings are made possible through realistic correction of outliers, often due to human data handling, rather than applying a worst case assumption.

The forecasting of engine support costs and justification of system modification and upgrade programmes demand the support of credible and effective LCC studies. The MTU LCC simulation model for maintenance, repair and operation is discussed in Paper 2 and clearly identifies the interdependence of various cost parameters impacting on the engine fleet. LCC calculations present similar multivariate optimisation challenges to those experienced in component design. Paper 5 discusses a formal method of coupling multi-disciplinary analysis with probabilistic methods and optimisation of design; a method that not only offers an exciting design route but also provides valuable experience of integrating established tools into an effective multi-level analysis suite.

Paper 11 provides a detailed briefing on the EJ200 engine monitoring and diagnosis system architecture and functionality; the discussion of lessons learned throughout the project is of particular value. As might be expected, the drive for increased functionality features strongly in potential development plans, however, the most significant recommendations are for a streamlined development process, with earlier EHM development and the inclusion of units in engine development and testing, and for greatly simplified system architectures and standardised interfaces.

Usage Data and Mission Analysis

Effective fleet management depends upon the timely receipt of accurate information on the state of health and usable life of the components throughout the system. Papers 7 and 8 focus on the health monitoring functions of vibration and wear debris analysis, and illustrate the benefits of applying new technology and advanced data processing to these established tasks. The vibration monitoring system claims to be achieving high quality results and has been designed with strong attention to reliability issues; a spurious indication has almost the same operational impact as a true fault but degrades confidence in the monitoring capability. The application of pattern recognition algorithms to wear debris analysis is being used to develop a consistent and reliable method of interpreting SEM/EDX results; such techniques are essential in minimising manual operator errors and provide insulation from experience gaps caused by changes in staff. However, it is interesting to note a point made during the presentation, that an operator guided system is necessary to overcome spot analysis errors and to manipulate debris to identify coating materials, ie the need to test each side of the particle.

Papers 9 and 10 discuss the optimisation and simplification of Gas Path Analysis (GPA); the first extends the singular value decomposition of the Jacobian matrix in an attempt to optimise the sensor suite necessary for health monitoring, and the second investigates the accuracy of multiple handle GPA as a method of both simplifying and speeding analysis routines. The integration of control and monitoring systems will undoubtedly lead to sensor selection being driven by both requirements and studies such as these are important to inform both the monitoring system retrofit community and the designers of new systems.

In Paper 12, discussion of the NASA Intelligent Life Extending Control (ILEC) programme applies the integration of control and monitoring to the mitigation of component damage during engine acceleration and cruise. The use of a control 'buffer' to lessen the impact of a demanded input is an emotive topic, however, through both theoretical and hardware in the loop simulation this project has shown significant reductions in engine damage in exchange for minor reductions in acceleration response or cruise Mach number. The philosophical arguments over placing a buffer between the pilot's demand and the engine's response will remain but this paper will contribute to the debate by quantifying what can be achieved from extending the role of on-board damage estimation to supervisory control of the engine.

Life Determination Methodologies

Papers 14 and 22 discuss genuine in-service lifing issues and illustrate both the latitudes and the limitations involved in the safe-life philosophy, on the one hand, the conservative analysis and large safety factors providing scope for life extension, and on the other the requirement for regular lifing reviews to ensure that the validity of assumptions has not been eroded by actual material, manufacturing and usage factors. The ability to address these particular cases depended on a significant understanding of design models, failure modes, material properties, and life assessment methodologies, and therefore, both papers demonstrate the importance of a degree of self-reliance in lifing capabilities to the management of military gas turbine fleets.

Whilst material properties, surface condition and operational exposure may detrimentally affect the usable life of a component, the ability to accurately monitor and record the life consumption rate is also imperative in achieving cost-effective utilisation of that life. Paper 15 and the paper entitled, 'The Assessment of Engine Usage Data', consider how to bridge data gaps to avoid the imposition of an expensive 'worst case' exchange rate filler. No monitoring system is successful in capturing 100% of the cycle counts, failures may be due to monitoring system faults, storage media damage and data corruption during transfer and, especially in the case where only a sample of the engine fleet is monitored, data loss can be significant. Large variability exists within usage data and there is often a poor correlation between mission duration and cycles counted, and between SPC and cycles counted. These papers provide guidance on the statistical methods that may be effective in extrapolating limited monitoring results.

A significant amount of work is being sponsored by the US Air Force in a programme designed to reduce the anticipated replacement cost of LLPs. Paper 16 considers crack propagation life extension, without increasing risk, by taking credit for residual stresses. Residual stress relaxation under operational exposure is discussed and the influence of various levels of retained residual stress on crack propagation is assessed. Development of this approach into a practical lifing methodology depends upon the availability of advanced NDI techniques capable of monitoring residual stresses. Papers 17 and 21 consider the influence of loading on crack propagation, the first assessing the effect of overload on subsequent damage accumulation, and the second assessing the influence of underloads on damage accumulation. These three papers should be read in conjunction to gain benefit from their contribution to the understanding of fatigue crack growth behaviour and their comment on the conservatism of current lifing methodologies.

Modern, high temperature, metallic materials present significant lifing challenges that demand advanced methodologies. Paper 20 describes the demonstration of an integrated analysis tool for the lifing of turbine components. The tool is capable of accepting data from on-board monitoring systems and comprises an engine gas path model, FEA for thermal distribution and mechanical loading, life modelling (LCF, creep, oxidation and crack growth) and has been applied to the lifing analysis of a film-cooled turbine blade. The results exhibited large uncertainty due to the inaccuracy of the life prediction model, especially in crack initiation and creep, caused by scatter in the material data. However, the tool has shown itself to be useful for relative life predictions and offers the potential to input to on-condition maintenance by tracking the life consumption of individual components and enabling optimisation of aircraft operational use through determination of life consumed in specific operational manoeuvres/sortie profiles; a feature that may contribute significantly to LCC calculations and 'what if' analyses for aircraft role change or fleet management of run-down to retirement.

The paper entitled, 'New Lifing Methodology for Engine Fracture Critical Parts,' states that the safe-life methodology is increasingly unable to cope with modern design complexities. A methodology employing non-linear 3-D FEA to calculate actual component stresses, modelling of both crack initiation and propagation phases, and accounting for the effect of material volume (size effect) is described. Prediction accuracy was seen to fall off at 600°C, prompting the need for a review of the fracture mechanics model, however, predictions show good agreement with a large proportion of the materials database and component predictions are encouraging. This work represents a significant achievement and will yield a valuable tool once a residual stress model has been incorporated and validation against other materials has been completed.

Paper 24 presents the results from development tests of a fatigue-creep-oxidation interaction model that shows much promise for the prediction of crack propagation in high temperature alloys. The crack propagation rate was over-predicted from simulated mission profile due to effect of minor cycles. The fatigue-creep-oxidation model

has been extended to account for complex loads in non-isothermal conditions but will also need some development to account for a wider temperature range.

DISCUSSION

The symposium sought to discuss monitoring and management of gas turbine fleets for extended life AND reduced costs, thereby setting a significant challenge to the contributors. It is without doubt that military gas turbine systems are required to remain in service for extended periods and the content of the papers has graphically illustrated that the replacement of LLPs constitutes a strong cost of support driver; over the next 20 years, disk replacement costs to for the US Air Force are expected to rise to \$3bn.

It is recognised that the management of engine fleets demanded large quantities of operational and maintenance data to support decision-making. Whilst large quantities of data are collected and stored, many of the databases have severe limitations that impact on their usage and ability to support data manipulation and extraction of relevant information. Material and usage data variability also hinders analysis and imposes expensive conservatism in lifing methodologies. More effort should be made in developing interfaces between databases and releasing the potential stored by the NATO member nations.

In monitoring for engine life management, there is a consensus view that full fleet monitoring is the optimal solution. The meeting drew out the importance of Thermal Transient Algorithms in realising life extension benefits and support cost reductions, a point strongly made in the RTO Technical Report 28. However, modifications to extend component life or to insert additional monitoring functionality can be very difficult to justify unless safety related. Life cycle cost modelling is essential in supporting the business cases for modification or upgrade and for evaluating the performance of the system following introduction. It would be of great benefit to increase the exchange of information on LCC analysis techniques and to develop common approaches to modelling.

It is also stressed that a modification often has much wider impact on the system than just at the point of application. The important conclusion is that the engine system, and that includes its monitoring functions, both airborne and ground-based, has to be considered as a whole system in assessing the potential impact of modifications and upgrades. The single largest monitoring system improvement desired was to simplify both the airborne and ground-based system architectures to eliminate the impact of multiple interfaces and obviate the need for human intervention in data handling, as this always carries an inherent error rate. The subject of storage capacity was considered to be one of development time versus technology risk and fell into the category of obsolescence management.

It is important to note that due to high non-linearity of usage data, extrapolation of results is difficult and can be dangerous, similarly, applying a worst case exchange rate to data gaps is overly conservative and consequently expensive. The application of plausibility ranges to identify nonsensical outliers and statistical processes to bridge the gap, relocate the outlier or quantify the risk is viewed as an essential feature of the monitoring system to minimise the risk of overruns and promote airworthiness.

It is considered that due to conservatism in the safe-life philosophy design and the simpler design and materials processing routes, there is much scope for component life extension for older, conventionally forged LLPs. To support life extension initiatives, there is an urgent need to develop greater understanding of crack propagation and there is a specific need for improvements in NDI techniques for both crack detection and for residual stress measurement. The symposium brought out the importance of self-reliance in lifing capabilities in enabling military gas turbine operators to manage in-service issues, this type of expertise may be difficult to preserve in a climate of cost reduction and privatisation of government laboratories.